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A Review of Major Storm Impacts on Coastal Wetland Elevations

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ABSTRACT: Storms have long been recognized as agents of geomorphic change to coastal wetlands. A review of recent data on soil elevation dynamics before and after storms revealed that storms affected wetland elevations by storm surge, high winds, and freshwater flushing of the estuary (inferred). The data also indicate that measures of sediment deposition and erosion can often misrepresent the amount and even direction of elevation change because of storm influences on subsurface processes. Simultaneous influence on both surface and subsurface processes by storms means that soil elevation cannot always be accurately estimated from surface process data alone. Eight processes are identified as potentially influencing soil elevation: sediment deposition, sediment erosion, sediment compaction, soil shrinkage, root decomposition (following tree mortality from high winds), root growth (following flushing with freshwater, inferred), soil swelling, and lateral folding of the marsh root mat. Local wetland conditions (e.g., marsh health, tide height, groundwater level) and the physical characteristics of the storm (e.g., angle of approach, proximity, amount of rain, wind speed, and storm surge height) were apparently important factors determining the storm's effect on soil elevation. Storm effects on elevation were both permanent (on an ecological time scale) and short-lived, but even short-term changes have potentially important ecological consequences. Shallow soil subsidence or expansion caused by a storm must be considered when calculating local rates of relative sea level rise and evaluating storm effects on wetland stability.

Introduction

Coastal wetlands develop in response to multiple interacting factors and feedbacks that control geomorphology, wetland surface elevation, habitat stability, and ecosystem function (Mitsch and Gosselink 2000). High frequency, low magnitude events or stressors (e.g., tides, cold fronts, seasonal and annual fluctuations in sea level, precipitation, river discharge, and groundwater fluxes) exert a regular and often predictable influence on ecosystem processes such as primary production, organic matter accumulation, materials exchange, and nutrient cycling (Day et al. 1995). Process interactions and feedbacks in coastal wetlands (e.g., tidal flooding patterns, sedimentation, plant productivity, soil elevation) allow wetland elevation to self-adjust to changes in sea level (Morris et al. 2002). Coastal wetlands are also influenced by low frequency, high magnitude events (i.e., tropical cyclones and El Niño storms), which exert acute, unpredictable effects, including short-lived but extreme increases in sea level (i.e., storm surge), precipitation, and wind speeds (Lugo 2000). These infrequent, high magnitude disturbances are geomorphologically and ecologically important because they can affect a large area (Yih et al. 1991), although with high spatial variability (Whigham et al. 1999), and their effects on vegetation and soils may be permanent on an ecological time scale (Wanless et al. 1994). Despite the great potential for these high magnitude disturbances to affect the suite of processes controlling coastal wetland soil elevation (e.g., sediment deposition and erosion, root growth, decomposition, and soil organic matter accumulation), little empirical data exist to evaluate the effect of major storms on coastal wetland soil elevations and long-term wetland stability relative to sea level rise.

Mechanisms by which storms affect coastal wetland soil elevation include substrate disruption and sediment redistribution by storm surge (Guntenspergen et al. 1995; Cahoon et al. 1995b; Nyman et al. 1995), acute tree mortality by high winds leading to loss of soil organic matter content (Cahoon et al. 2003a), and delivery of massive quantities of sediment to coastal wetlands by severe upland runoff or erosion induced by extreme precipitation (Cahoon et al. 1996, 2003b). To a lesser extent, storms may influence soil elevation through decreases in soil organic matter content when the surge of seawater far inland adversely affects the growth of freshwater plants (i.e., salt burning, which potentially lowers soil elevation; Guntenspergen et al. 1995) or increases in root growth (which potentially raises soil elevations) by flushing the estuary with large amounts of freshwater from precipitation and upland runoff.

Hurricane storm surges can cause large-scale redistribution of sediments resulting in sediment deposition, erosion, compaction, disruption of vegetated substrates, or some combination of these processes (Morgan et al. 1958; Cahoon et al. 1995b;

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Guntenspergen et al. 1995; Nyman et al. 1995; Risi et al. 1995). Extreme winds can defoliate and topple mangrove trees, and in combination with storm surge, result in mass mortality of mangrove forests (Jimenez et al. 1985). Death of a mangrove forest can lead to substrate collapse as dead roots decompose in the absence of new root growth (Cahoon et al. 2003a). Extreme precipitation can cause local rivers to jump their channels and carve new channels through the upland, mobilizing millions of tons of sediment that are deposited in downstream wetlands, such as occurred in the Tijuana River during the 1993 El Niño storm in southern California (Cahoon et al. 1996) and the Choluteca River on the Pacific coast of Honduras during Hurricane Mitch in 1998 (Cahoon et al. 2003b).

Although the effects described above are readily observable, and sediment deposition, erosion, and tree mortality are often measured after storms, rarely have storm effects on wetland elevation been measured directly. A preliminary review of the literature through 2001 by Cahoon (2003) revealed that storm-induced soil elevation change followed one of three patterns: elevation change equivalent to sediment deposition or erosion, elevation loss despite sediment deposition or greater than erosion, and elevation gain greater than sediment accretion or despite erosion. These findings suggest that storms influence soil elevation through their effects on both surface and subsurface processes. Cahoon (2003) identified eight processes related to storm effects as potentially controlling soil elevation of a wetland. These included the surface processes of sediment deposition and sediment erosion; the subsurface processes of sediment compaction, soil shrinkage (soil water drainage), post-storm peat decomposition, post-storm root growth (inferred), soil swelling (soil water storage), and a process that is not simply a surface or subsurface process—the rending and folding of the rooted marsh mat.

This paper reviews the literature on direct measures of major storm effects to wetland vertical accretion and soil elevation through the 2005 hurricane season, and assesses how storms influence surface and subsurface soil processes. The implications of these findings for long-term wetland stability are discussed.

Methods

The surface elevation table-marker horizon (SET-MH) method (Cahoon et al. 1995a, 1999, 2002a,b) was most commonly used to collect the vertical accretion and soil elevation data reviewed in this paper. The data were collected mostly before and after major storm landfalls, with post-storm data collected 2–12 wk after the storm. The storm effect was assessed by comparing pre-storm and post-storm data and changes during the storm interval with the long-term trends for accretion and elevation. The multiyear trends in accretion and elevation for most sites are presented graphically in Cahoon (2003), Cahoon et al. (1998, 2003a), and Rybczyk and Cahoon (2002). At Guanaja, Honduras, and Florida, USA, no pre-storm data were collected but post-storm data were collected for a minimum of 1–2 yr. At Guanaja, data were collected by the SET-MH method (Cahoon et al. 2003a), and in southwest Florida from deep rods inserted into the substrate (Wanless unpublished data). Elevation of laterally torn and folded marshes in coastal Louisiana was monitored with standard survey methods after each storm passage.

The SET-MH method simultaneously measures vertical accretion and soil elevation change with high precision (1–2 mm, Cahoon and Turner 1989; Boumans and Day 1993; Cahoon et al. 2002a,b). Measures of vertical accretion from a soil marker horizon integrate several processes (e.g., sediment deposition and erosion, root growth) occurring at the marsh surface or in the top few millimeters or centimeters of the soil (Reed and Cahoon 1993). Subsurface processes include all processes occurring below the marker horizon but above the base of the SET benchmark. The separate contribution of surface and subsurface processes to soil elevation is determined by comparing SET and soil marker horizon data (Cahoon et al. 1995a, 1999). The collective influence on soil elevation of subsurface processes (e.g., root growth and decomposition, sediment compaction, and shrink or swell from soil water flux) occurring between the marker horizon and the bottom of the SET benchmark (3–25 m deep) is called shallow subsidence (SS), which is calculated as vertical accretion (A) minus elevation change (E). Subsurface process influences on elevation are negligible and surface processes control elevation when $E = A$, with sediment deposition leading to a positive change and erosion leading to a negative change. Elevation is affected, and in some cases controlled, by subsurface processes when $E > A$ or $E < A$, even if A is positive. When $E < A$, elevation is likely affected singly or in combination by sediment compaction, organic matter decomposition, and soil shrinkage (related to water drainage). But when $E > A$, elevation is affected by root growth, soil swelling (related to water storage), and lateral tearing and folding of vegetated marsh substrate.

Determining empirically which subsurface process controlled elevation change in the time frame of the post-storm sampling interval (2–12 wk) at each site requires additional process-oriented measurements, which were usually not available. It was often possible to qualitatively ascertain which subsurface process was the likely driver of elevation change from an assessment of substrate characteristics and the types and degree of storm effects. For example, SS is typically driven by sediment compaction, organic matter decomposition, or soil shrinkage. Most mangrove sites reviewed in this analysis suffered severe tree mortality, so decomposition would be an expected driver of elevation loss. All marsh sites experienced no storm-related plant mortality, with the exception of the torn-folded-displaced marshes, so decomposition is less likely to be a driver of marsh elevation loss. The marsh substrates have the potential to be compacted by the weight of the overlying storm surge waters because of air trapped in soil pore spaces even when the marsh surface is inundated. The presence of an aerated layer near the soil surface is well documented (see Chapman 1974, p. 60–63, and Ranwell 1972, p. 92–95, for reviews of this topic). The squeezing out of air from this shallow aerated layer by the weight of the storm surge overburden could explain observed compaction rates. Regasification of this shallow aerated layer by microbial activity also could explain the rebound in elevation observed at some sites following a storm.

In all cases, accretion and elevation rates within a given study and over the same study period were compared statistically, either through *t*-tests (e.g., comparison of regression parameters) or through analysis of covariance. A five percent Type I error was used in these models.

Results

A total of 26 elevation responses to 15 storms from 17 sites are presented in Tables 1 and 2. All but one of the storms was a tropical cyclone with either tropical storm (TS) or hurricane force winds. The remaining event was an El Niño storm that brought extreme amounts of precipitation to the Tijuana River watershed in 1993. Pre-storm and post-storm data were available for 18 of the responses, while only post-storm data were collected at the laterally folded marshes in Louisiana and the mangrove forests of southwest Florida (after Hurricane Andrew) and Guanaja. Storms affected wetland elevations by three mechanisms: storm surge, high winds, and freshwater flushing of an estuary (inferred). Storm surge caused direct and immediate changes to soil elevation by effects to both surface and subsurface soil processes, and was the primary mechanism driving elevation change in 23 out of 26 responses. High winds combined with storm surge resulted in mangrove forest mortality (defoliation and toppling of trees) at two sites (southwest Florida and Guanaja), which resulted in a post-storm loss of elevation through soil organic matter oxidation. Flushing of the hypersaline high marsh at Tijuana Slough by extensive freshwater river flooding caused by extreme precipitation and runoff resulted in elevation gain by a purported increase in root growth.

Both surface and subsurface processes positively and negatively influenced soil elevation. The data indicate that storms directly affected soil elevation through sediment deposition, erosion, and compaction, soil water flux (both shrink and swell), and lateral tearing and folding of vegetated substrate. Storms indirectly affected soil elevation of mangrove forests by the elimination of root growth through tree death, and of hypersaline high marsh by enhancement of root growth by flushing with freshwater. For some sites, the effect processes and the elevation response varied among storms.

Surface Process Controls (E = A)

Six wetland elevation responses did not differ ($p > 0.05$) from the amount of sediment deposited or eroded by the storm surge, indicating that surface processes controlled elevation at these sites during these storms (Table 1). Sediment deposition controlled elevation at three different saline wetland types, while storm surge removal of sediment twice decreased elevation at a *Juncus* marsh and an intertidal mudflat. The elevation of the mudflat at Big Sable Creek in the Everglades was 32 mm lower after Hurricane Wilma (2005). Although no direct measure of erosion was made, erosion of the mudflat is inferred from the 7-yr data record where the marker horizons disappeared immediately after being established and the elevation trend has been consistently negative (Smith unpublished data). The possibility cannot be discounted that the Hurricane Wilma storm surge both compacted and eroded the poorly consolidated sediments of the mudflat.

Subsurface Process Controls

Subsurface processes controlled the majority of wetland elevation responses to storm effects, as indicated by the instances where E and A were different ($p < 0.05$; Table 1).

Elevation Loss (E < A)

The most commonly measured response (12) to storm effects was E < A (Table 1). Sediment compaction by storm surge was the most common process (7) causing this response. A common feature of these wetlands is that they are either highly deteriorated (e.g., Bayou Chitigue and Blackwater National Wildlife Refuge [NWR]) or have a high organic matter content, or both. The highly deteriorated, low shear strength, *Spartina*

TABLE 1. Assessment of processes controlling wetland surface elevation responses to storm effects.

Elevation Response	Process	Site	Wetland Type	Before/After Data	Storm	Accretion (+) or Erosion (−) (mm)	Elevation Change (mm)	References
E = A	Sediment deposition	Old Oyster Bayou, Louisiana	*Spartina* salt marsh	Yes	H. Andrew 1992	+20	+23	Cahoon et al. 1995a,b, 1999
		Ochlockonee – Bald Point, Florida	*Juncus* salt marsh	Yes	H. Erin 1995	+5	+4	Hendrickson 1997
		Big Sable Creek, Florida	Mangrove	Yes	H. Wilma 2005	+1	+4	Smith unpublished data 2005, 2006
	Sediment erosion	St. Marks River, Florida	*Juncus* salt marsh	Yes	H. Allison 1995	−1	−1	Cahoon et al. 1999
		St. Marks River, Florida	*Juncus* salt marsh	Yes	H. Erin and Opal 1995	−6	−5	Hendrickson 1997
		Big Sable Creek, Florida	Mudflat	Yes	H. Wilma 2005	not measured	−32	Smith unpublished data 2005, 2006
E < A[a]	Sediment compaction	Bayou Chitigue, Louisiana	*Spartina* salt marsh	Yes	H. Andrew 1992***	+28	−5	Cahoon et al. 1995a,b, 1999
		Cedar Island, North Carolina	*Juncus* salt marsh	Yes	H. Emily 1993***	+3	−3	Cahoon et al. 1995a
		Cedar Island, North Carolina	*Juncus* salt marsh	Yes	H. Gordon 1994**	+3	−3	Cahoon et al. 1998
		Cedar Island, North Carolina	*Juncus* salt marsh	Yes	H. Felix and T. S. Jerry 1995***	−1	−18	Cahoon et al. 1998
		Cedar Island, North Carolina	*Juncus* salt marsh	Yes	H. Dennis 1999*	+8	+3	Cahoon 2003
		Blackwater NWR, Maryland	*Spartina* brackish marsh	Yes	H. Isabel 2003*** Eastern Refuge** Western Refuge[ns]	+9 +12 +3	+2 +4 −0.4	Cahoon unpublished data Cahoon unpublished data Cahoon unpublished data
		Shark River, Florida	Mangrove	Yes	H. Wilma 2005[b]	+77	+48	Smith unpublished data 2005, 2006
	Soil shrinkage	St. Marks River, Florida	*Juncus* salt marsh	Yes	TS Beryl 1994***	−1	−21	Cahoon et al. 1999; Cahoon 2003
		Ochlockonee – Bald Point, Florida	*Juncus* salt marsh	Yes	H. Opal 1995**	−1	−14	Hendrickson 1997
		Ochlockonee – Turtle Island, Florida	*Juncus* salt marsh	Yes	H. Erin 1995[c]	+5	−13	Hendrickson 1997
	Peat decomposition	Southwest Florida	Mangrove	After only	H. Andrew 1992	not measured	−20 mm yr^{-1}	Wanless unpublished data
		Guanaja, Honduras	Mangrove	After only	H. Mitch 1998***	+2 mm yr^{-1}	−9 mm yr^{-1}	Cahoon et al. 2003
E > A	Root growth (inferred)	Tijuana Slough, California	*Salicornia* salt marsh	Yes	El Niño storm 1993**	+1	+4	Cahoon et al. 1999; Cahoon 2003
	Soil swelling	St. Marks River, Florida	*Juncus* salt marsh	Yes	TS Alberto 1994***	+3	+19	Cahoon et al. 1999; Cahoon 2003

[a] Differences between means are significant at * ($p = 0.107$), ** ($p < 0.05$), and *** ($p < 0.01$); or nonsignificant (ns).
[b] Statistical test was not performed, but difference between means is large and standard errors are small: 77 (1.6) mm versus 48 (1.8) mm.
[c] Raw accretion data were not available to test for differences in means.

TABLE 2. Tearing and folding of coastal marsh root mat by hurricane storm surge in Louisiana.

Site	Storm	Tearing (m)	Folding (m)	References
Otter Bayou, Louisiana	H. Andrew 1992	−0.5*	+0.5 to +0.75	Cahoon unpublished data
West Terrebonne	H. Andrew 1992	−0.5*	+0.66 to +2.1	Guntenspergen et al. 1995
West Cote Blanche	H. Lili 2002	−0.5 to −1.3	+0.5 to +2.0	Barras 2003
Caernarvon	TS Isidore 2002	−0.5*	+0.5*	Barras unpublished data
Caernarvon, Pearl River, Mississippi delta	H. Katrina 2005	−0.5*	+0.5*	Barras unpublished data
West Cote Blanche Freshwater Bayou	H. Rita 2005	−0.5*	+0.5*	Barras unpublished data

*Minimum estimate, change in elevation (m) not directly measured.

alterniflora marsh substrate at Bayou Chitigue was compacted by the weight of the storm surge waters and lost 5 mm of elevation despite 28 mm of sediment deposition. The highly deteriorating and organic marsh substrate at Blackwater NWR was compacted 7–8 mm so that elevation gain lagged behind vertical accretion (Table 1). Sediment deposition and compaction was greater in the area of the refuge closest to an open bay. At Cedar Island, the nearly 20 mm of compaction measured 3 wk after Hurricane Felix and TS Jerry (instead of the 12–15 wk for the other storms monitored at Cedar Island) suggests that the compaction of the highly organic substrate is initially > 20 mm but the surface rebounds so that a few months after the storm the compaction is only a few millimeters, as recorded for the other storms. The mechanism by which the compacted substrate expands and the surface elevation rebounds is not known, although regasification of the substrate (soil interstices and organic matter lacunae) by microbial activity would be plausible if compaction was caused by degasification of the substrate. Hurricane Wilma deposited 77 mm of sediment on average in the mangrove forest at Shark River, but soil elevation gain was 29 mm less than accretion (Smith unpublished data). The main driver of this SS was likely sediment compaction, although this substrate shrinks and swells with groundwater level (Whelan et al. 2005), so soil shrinkage cannot be ruled out as a mitigating process. Soil organic matter decomposition also cannot be ruled out as a contributor to elevation loss but it is a less likely driver of the c. 3 cm of SS because sampling occurred within 3 wk of the storm and there was no mass tree mortality (Smith unpublished data, report a 50% defoliation of the canopy) that would have resulted in a complete cessation of root growth. This site warrants additional elevation monitoring. If the forest health continues to degrade and tree mortality occurs, decomposition (i.e., peat collapse) could become a primary driver of continued elevation loss.

The elevation loss in three *Juncus roemerianus* salt marshes in the Big Bend of Florida may have been caused by sediment compaction, but soil shrinkage is a more reasonable explanation (Cahoon 2003). A 20 mm decrease in elevation over the 2-mo sampling interval that included TS Beryl followed a nearly 20 mm increase in elevation over the previous 2-mo sampling interval that included TS Alberto (Table 1, E > A). This large fluctuation in elevation during the middle of the plant growing season strongly suggests that shrink-swell of the substrate related to changes in the water table of this karst setting caused the elevation change rather than sediment compaction or changes in root growth. What role each storm may have played in groundwater dynamics through precipitation patterns and storm surge is not clear given the lack of groundwater monitoring.

The immediate effect of high winds and storm surge on mangrove forests in Florida and Guanaja by Hurricanes Andrew and Mitch was to cause mass tree mortality. The long-term effect of this mortality was a steady decline in soil elevation over the next several years through oxidation of the root mat in the absence of new tree root growth.

Elevation Gain (E > A)

After 9 yr of drought and no appreciable river flow, the elevation of the hypersaline soils of the *Salicornia subterminalis*-dominated high salt marsh at Tijuana Slough responded positively to several large river flood events related to an El Niño Southern Oscillation, with elevation exceeding sediment deposition (Table 1). Cahoon et al. (1999) hypothesized that the flushing of the hypersaline soils with freshwater improved soil conditions for plant growth, which led to increased root growth and an increase in soil elevation during the 2-mo interval between the storm and the time of post-storm sampling. The measured decrease in soil elevation the year following the storm was the likely result of decomposition and reduced root growth when drought and hypersaline soil conditions returned (Cahoon et al. 1999; Cahoon 2003). Soil swelling is an unlikely cause of the elevation increase given the high sand and low organic matter content of the soil.

Tearing and Folding of the Marsh Substrate

In coastal Louisiana, hurricane storm surges have been reported to move the intact marsh root mat

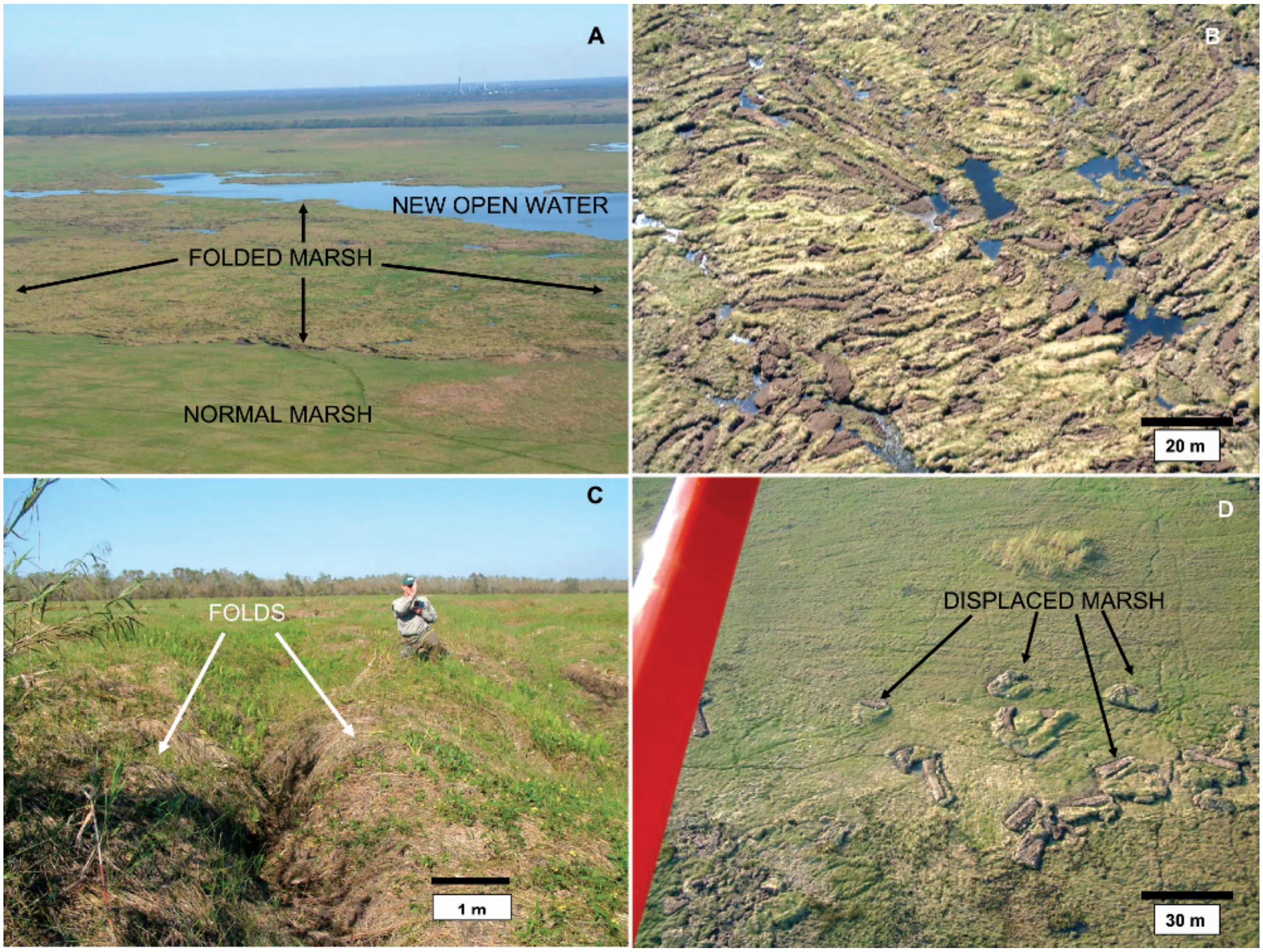

Fig. 1. The Hurricane Lili storm surge tore and folded the marsh root mat in coastal Louisiana (photo coordinates: 29°40′N, 91°36′W; date of photographs: Novemeber 7, 2002). A) Aerial oblique view showing extent of folded marsh in relation to normal marsh, and creation of new open water by tearing. (Based on a maximum fold height of 1.5 m, the leading edge of the folded marsh shown in the foreground is estimated to be approximately 500 m wide. Note that the leading edge extends beyond the borders of the photograph.) B) Aerial perpendicular view of folded marsh root mat. C) Ground view of folded marsh root mat. D) Displaced blocks of marsh root mat deposited on the marsh surface. (Photograph credits: Thomas Michot and Christopher Wells, U.S. Geological Survey, National Wetlands Research Center.)

located directly within the water flow path (tens to hundreds of meters wide; Guntenspergen et al. 1995), like pushing a throw rug across a wooden floor (Fig. 1). This action has two immediate effects on marsh soil elevation. The area from which the marsh mat is torn away is immediately converted to open water with a depth equal to at least the thickness of the root mat (c. 0.5 m) or greater if scour occurs during storm surge and retreat. The root mat will move laterally until it hits an obstruction (e.g., ridge or levee), at which time it begins to fold like an accordion. The height and frequency of the folds are directly related to the force of the storm surge and the size of the marsh root mat.

When the root mat stops its lateral movement, the trailing edge of the root mat is often torn by the storm surge into rectangular pieces several tens of meters long, half again as wide, and c. 0.5 m thick (Fig. 1). These pieces of marsh are typically thrown onto the surface of the root mat, marsh side up or inverted, sometimes stacked 2 or 3 high. Louisiana scientists coined the term ‘‘displaced marsh’’ to describe these marsh blocks because of their location on top of the original root mat (Michot et al. in press). Guntenspergen et al. (1995) referred to the process of lateral marsh movement as lateral compression of the marsh. In this paper, I refer to it as tearing and folding because the marsh root mat is first torn apart (creating open water) and then folded and displaced (creating supratidal marsh elevations). Table 2 presents both negative (tearing) and positive (folding and displacing) changes to marsh elevation as a consequence of marsh root mat movement.

In 1992, the Hurricane Andrew storm surge caused extensive marsh folding in western Terrebonne Parish, Louisiana. At Otter Bayou, lateral folding of the substrate resulted in a 0.5–0.75 m increase in elevation over a lateral distance of $<$ 0.5 m (Cahoon unpublished data). During a 6-mo period in 1993, the tops of the folds accreted vertically 10 mm, while the folds lost 15 mm of elevation through compaction (Guntenspergen et al. 1995). Elevation of the ridge tops at Otter Bayou declined steadily for 2 yr to pre-storm levels and then increased until E = A after 3 yr (Cahoon unpublished data). Elsewhere in western Terrebonne Parish, lateral folding of the substrate by Hurricane Andrew resulted in ridges 0.66–2.10 m high with intervals between ridges of 2–5 m (Guntenspergen et al. 1995).

In 2002, Hurricane Lili created 257 ha of open water, with a depth of 0.5–1.3 m, at West Cote Blanche, Louisiana, by the lateral movement of the marsh root mat (Barras 2003). Displaced blocks of marsh, sometimes stacked 2 and 3 high (Steyer personal communication), and marsh folds resulted in soil elevation increases ranging from 0.5 to $>$ 1.5 m (Barras 2003). In other parts of the coast, the Hurricane Lili storm surge reactivated some of the old Hurricane Andrew tearing and folding. Remotely sensed data acquired and analyzed by the U.S. Geological Survey, National Wetlands Research Center (Barras unpublished data) reveals that storm surges from the following storms caused extensive folding: TS Isidore (2002) in the Caernarvon marshes south of New Orleans, Hurricane Katrina all along its track, but especially in upper Breton Sound and the Pearl River area, and Hurricane Rita in the Freshwater Bayou and Lake Boudreaux areas, in addition to reactivation of some of Hurricane Lili folds (e.g., West Cote Blanche). No ground truth data or measurements are available for these affected regions, but a minimum estimate of soil elevation change would be $\pm$ 0.5 m.

Discussion

Controls on Elevation

Subsurface processes affected 14 of 20 and controlled 11 of 20 soil elevation responses (Table 1). A controlling influence on a response is indicated when the subsurface process changes the sign of the response (i.e., accretion is positive but elevation change is negative) or when elevation change greatly exceeds accretion or erosion. When both accretion and elevation are positive but elevation change is lower, the subsurface process mitigates the surface accretionary effect but does not dominate the response. These data clearly show that subsurface process effects on wetland elevation must be considered when evaluating a storm's effect on wetland stability and sustainability. Predicting subsurface process influences by storms on wetland elevation is not simple because the influences varied widely among sites and storms. Compaction by storm surge ranged from 3 to 33 mm and soil shrinkage ranged from 13 to 20 mm (Table 1). The process controlling soil elevation in an individual marsh sometimes varied among storms (e.g., soil shrinkage, swelling, and erosion at St. Marks).

In order to predict a storm's effect on soil elevation, a better understanding is needed of the factors influencing the response, such as marsh type and health, local conditions at the time of the effect (e.g., tide height, groundwater level), and the physical characteristics of the storm (e.g., angle of approach, proximity, amount of rain, wind speed, storm surge height). To provide a preliminary determination of the factors most likely controlling wetland elevation response to a storm, elevation responses were analyzed for replicate marsh types and multiple storm effects to the same marsh. Excluding the vegetationally diverse, laterally-folded marsh areas of the Louisiana coast, three wetland types are represented multiple times in the elevation response data set: *J. roemerianus* high salt marsh (11), mangrove forest (4), and *Spartina* low salt marsh (3). Four storm strikes were measured at both St. Marks and Cedar Island and two strikes at Ochlockonee-Bald Point *J. roemerianus* marshes. In the low wave energy, karst setting of the Big Bend of Florida (i.e., Appalachee Bay), 7 elevation responses were measured in the three *J. roemerianus* marshes (St. Marks, Ochlocknee-Bald Point, Ochlocknee-Turtle Island).

The highly organic substrates (typically $>$ 50% organic content by weight) of *J. roemerianus* marshes were the most reactive to storm surges, with subsurface processes affecting 8 of 11 responses and controlling 7. The Cedar Island marsh substrate (ca. 60% organic matter content) located in a highly protected (back barrier), low energy (microtidal, $<$ 5 cm tide range) setting was compacted 5–17 mm by four different storm surges. The three *Juncus* marsh substrates located along the low wave energy, karst shoreline of Appalachee Bay lost elevation by erosion (3 responses) and soil shrinkage (3 responses), and gained elevation by soil swelling (1 response). A dominant factor controlling elevation of these marsh substrates appears to be groundwater dynamics of this spring fed, limestone based setting (Cahoon 2003). Although the process response to each of four storms was the same at Cedar Island marsh, the process response to four storms by St. Marks marsh varied (erosion: 2, shrinkage: 1, and swelling: 1), as did the response to two storms by Ochlockonee-Bald Point marsh (erosion: 1 and shrinkage: 1). The variety of responses by the Appalachee Bay marshes may be related to how the storms affected groundwater dynamics through the amount of precipitation, runoff, and groundwater recharge. Additional data is needed to confirm the role of groundwater in elevation response.

Mangrove forest elevation response to storm surge effects differed importantly from the response to wind effects. The storm surge from Hurricane Wilma deposited sediments at both Shark River and Big Sable Creek forests. The elevation response was equal to the sediment deposit at Big Sable Creek but lagged behind sediment deposition at Shark River, apparently as a result of compaction. Groundwater level changes can directly influence soil elevation in the Shark River mangroves (Whelan et al. 2005), so the difference between accretion and elevation may have been related to groundwater changes during or immediately after the storm but prior to elevation measurements 2 wk after the storm. In contrast to the immediate and direct storm surge controls on elevation by sediment deposition and sediment compaction, high winds controlled elevation indirectly by stopping soil organic matter accumulation through mass tree mortality and post-storm root decomposition in the absence of root growth.

The elevation response of *Spartina*-dominated salt marsh substrates was correlated with marsh health and integrity. The deteriorated marsh substrates at Bayou Chitigue and Blackwater NWR both experienced sediment compaction in spite of sediment deposition, with Hurricane Andrew compacting the severely degraded *S. alterniflora* marsh substrate at Bayou Chitigue by 33 mm. The healthy substrate of the *S. alterniflora* marsh at Old Oyster Bayou, Louisiana, was not compacted by Hurricane Andrew, but instead gained elevation equal to the thickness of sediment deposits. Differences in the amount of compaction between the eastern and western sides of Blackwater NWR were related to marsh health and local setting. Marshes on the eastern side of the refuge were more deteriorated and more exposed to storm surge and reworked sediments from Fishing Bay.

The degree of sediment mobilization and sediment compaction was usually related to the intensity of the storm surge and the local geomorphic setting in relation to the storm track. Hurricane Dennis made landfall near Cedar Island, and the storm surge deposited the thickest sediment deposits of all the Cedar Island storms, as well as extensive wrack at the tree line and across roads. All other storms, which never made landfall at Cedar Island but pushed Pamlico Sound waters onto the marsh at Cedar Island (Cahoon 2003), mobilized less sediment but the storm surge still compacted the substrate. Marshes on the eastern side of Blackwater NWR (12 mm of sediment deposition and 8 mm of compaction) were directly exposed to surge waters from Fishing Bay as Hurricane Isabel moved north up Chesapeake Bay, while the marsh on the western side (3 mm of sediment deposition and compaction) was more protected from the surge. During Hurricane Wilma, the storm surge traveled up Shark River into the riverine mangrove forests (77 mm of sediment deposition). But the forests at Big Sable Creek (1 mm of sediment deposition) were located on the lee side of Cape Sable and were more protected from the surge.

Implications for Wetland Stability

A single low frequency, high magnitude storm can deposit more sediment on a marsh than an entire year of high frequency, low magnitude cold fronts (Cahoon et al. 1995b). Low-frequency sediment pulsing events such as hurricane storm surges are postulated to be critical for maintaining wetland soil elevation in sediment-poor settings with high rates of subsidence (e.g., the Mississippi River Delta; Rejmanek et al. 1988, Cahoon et al. 1995a,b; Day et al. 1995; Reed 2002). Yet this review of 26 elevation responses from a variety of hurricane-influenced coastal settings indicates that a storm can simultaneously influence both surface and subsurface soil processes with the net outcome on soil elevation not always predictable solely from the observed effects of sediment deposition and erosion. This influence on subsurface processes appears to be the single most important difference between high frequency, low magnitude and low frequency, high magnitude events. The implications for assessing wetland sustainability relative to future increases in sea level can be significant (Rybczyk and Cahoon 2002; Cahoon et al. 2006), especially given that the recently increased level of Atlantic hurricane activity is expected to continue for the next several decades (Goldenberg et al. 2001) and the intensity of future hurricanes is predicted to increase (Giorgi et al. 2001).

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